EVIDENCE FOR THE SLOW-NEUTRON GAMMA-FISSION REACTION IN Pu^{238} †

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The compound nucleus formed in slow-neutron bombardment of a heavy nucleus may decay by neutron emission, by electromagnetic radiation, or by fission. When the nucleus decays by the emission of a gamma ray, the secondary compound nucleus which results may still be left with enough energy for fission to compete with further gamma radiation, provided a fission channel is open for the different spin and parity of the new compound nucleus. This reaction, which has been called the slow-neutron, gamma-fission reaction, was first discussed in the literature by Stavinsky and Shaker,[1] who estimated that this reaction was nearly of the same order of magnitude as the total radiation width for those nuclei which undergo fission with thermal neutrons. However, Lynn[2] has concluded that this reaction is only about 5 or 10% of the total radiation width. No experimental evidence for this reaction has been reported. If the reaction is only as large as Lynn predicts, it would be very difficult to detect in the thermally fissionable nuclei, since the width for ordinary fission is at least an order of magnitude larger. However, the effect could be much stronger relative to ordinary fission in those nuclei for which fission through channels accessible by s-wave neutron absorption is strongly inhibited. If the spin and parity of the initial compound nucleus are transformed by the emission of a gamma ray to new values for which a fission channel is open, fission via the $(n,\gamma f)$ mechanism could compete strongly with ordinary fission.

Vorotnikov et al.[3] have studied the angular distribution of the fission fragments resulting from fast-neutron bombardment of Pu^{238} and concluded that fission induced by s-wave neutrons is strongly inhibited compared with that by p-wave neutrons. Thus, for this nucleus, fission from states with $J^\pi=\frac{1}{2}^+$ is strongly forbidden compared with fission from states with $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$. Katz, Baerg, and Brown[4] have investigated the photofission cross section of Pu^{239} and observe a plateau in this cross section below the neutron binding energy. If we assume that the interaction of a gamma ray with the Pu^{239} nucleus is primarily by electric dipole absorption, the $I^\pi=\frac{1}{2}^+$ state of the target is transformed to $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$ state. Therefore both experiments seem to indicate that fission can occur through these channels below the neutron binding energy. It would appear, then, that Pu^{238} might be an ideal target in which to search for this reaction. We might even expect that resonance fission proceeds predominantly by the $(n,\gamma f)$ mechanism.

This mechanism can probably be most easily distinguished from ordinary fission by analyzing the distribution of fission widths in the slow-neutron resonances. It has been known for some time that the wide fluctuation in fission widths among resonances is characteristic of the fission process through only a few channels.[5] However, these wide fluctuations are not expected to be present for $(n,\gamma f)$ fission. The probability of finding a fission width of some particular size for any level of the secondary compound nucleus is described by the Porter-Thomas[6] distribution with only a few degrees of freedom, i.e., characterized by a wide fluctuation in the magnitude of the widths. However, the apparent fission width for the initial state depends on a sum over the fission widths, weighted by the gamma-ray transition probability between the initial and secondary states, of all the secondary compound-nucleus states reached directly by gamma radiation from the initial state. The width fluctuations of the Porter-Thomas distribution, therefore, are averaged in this summing process. Thus, the observed width distribution should be narrow and characterized by a large number of channels.

Recent measurements on Pu^{238} have made possible the analysis of the fission-width distribution for the lowest energy slow-neutron resonances. The fission cross section has been measured[7] at the Lawrence Radiation Laboratory in Livermore, using the electron linear accelerator as a pulsed neutron source. Individual resonances have been resolved up to 125 eV, and area analysis based on the Breit-Wigner single-level formula has been applied to the data to extract values for $\Gamma_n{}^0\Gamma_f/\Gamma$. The total cross section has been measured recently, using the fast chopper facility of the Materials Testing Reactor located at Idaho Falls.[8] The resolution and sensitivity of the total cross-section measurement were somewhat superior to that of the fission cross section. The application of area analysis to these data yields values for $\Gamma_n{}^0$. An average value of 38 eV for the capture width Γ_γ is obtained from total cross-section measurements on the first three lowest-energy resonances. With this value it is possible to obtain values for the fission width when the fission and total cross-section measurements are combined. These calculations can be performed assuming either $\Gamma=\Gamma_\gamma+\Gamma_n+\Gamma_f$ or $\Gamma=\Gamma_\gamma+\Gamma_n$. Since the fission cross section is so small compared with the capture cross section, either assumption will give nearly the same result for Γ_f. Of course, the latter assumption implies that all fission proceeds via the $(n,\gamma f)$ reaction. The results of the measurements and the calculations for Γ_f, using the latter assumption, are given in Table I. Fission was observed in all resonances below 125 eV, except that at 59.8 eV. The upper limit for $\Gamma_n{}^0\Gamma_f/\Gamma$ was used to compute a value of Γ_f for this resonance. Using Wilets's method,[9] we may estimate the number of effective channels ν_{eff} by analyzing the distribution of fission widths of column four of the table. He gives the expression

$$\nu_{\mathrm{eff}}=2\langle\Gamma_f\rangle^2/[\langle\Gamma_f{}^2\rangle-\langle\Gamma_f\rangle^2],$$

and estimates the relative error to be

$$(\delta\nu_{\mathrm{eff}}/\nu_{\mathrm{eff}})^2$$
$$=n(\Gamma_2-\Gamma_1{}^2)^{-2}\{(\delta\Gamma/\Gamma)^2(\Gamma_4-2\Gamma_2\Gamma_3/\Gamma_1+\Gamma_2{}^3/\Gamma_1{}^2)$$
$$+\tfrac{1}{4}(\Gamma_4-\Gamma_2{}^2)-\Gamma_2\Gamma_3/\Gamma_1+\Gamma_2{}^3/\Gamma_1{}^2\},$$

where n is the number of resonances and $\Gamma_i=\langle\Gamma_f{}^i\rangle$. The percent error in the measurement of each width is assumed to be the same and equal to 25%. Using these relations, we find $\nu_{\mathrm{eff}}=7\pm1.7$. If we assume $\Gamma=\Gamma_n+\Gamma_f+\Gamma_\gamma$, we find $\nu_{\mathrm{eff}}=6\pm1.5$.

Table I. Resonance parameters of Pu^{238}.

Resonance energy (eV)	$\Gamma_n{}^0\Gamma_f/\Gamma$ [a] (meV)	$\Gamma_n{}^0$ [b] (meV)	Γ_f (meV)	Γ_γ [b] (meV)
2.91	0.0014	0.043	1.2	38
10.06	0.0120	0.067	6.8	38
18.7	0.0307	0.81	1.6	38
59.8	<0.015	0.21	3.0	38
70.2	0.051	0.25	8.2	38
83	0.136	1.65	4.4	38
110	0.09	0.7	5.8	38
114	0.11	0.97	5.5	38
119	0.10	2.9	2.4	38
122	0.30	2.1	8.7	38
Av.			4.75	38

[a] Obtained from fission–cross-section measurements at Lawrence Radiation Laboratory, Livermore, California.

[b] Obtained from total–cross-section measurements at Idaho Nuclear Corporation, Idaho Falls, Idaho.

A similar type of analysis, sometimes with graphical methods, has been applied to the nuclei U^{233}, U^{235}, Pu^{239}, Pu^{241}, Am^{241}, and U^{232}, all of which seem to indicate no more than two effective channels per spin state. We feel that the value of seven effective channels per spin state obtained for Pu^{238} is statistically significant and provides strong evidence that $(n,\gamma f)$ fission is present in Pu^{238}. It should be pointed out that if fission proceeds almost exclusively by this mechanism, then the fission-width distribution would be sharply peaked around the average value. Any uncertainty in determining the values for Γ_f would tend to broaden the distribution and reduce the apparent number of channels. Therefore, if the $(n,\gamma f)$ reaction actually is predominant in Pu^{238}, the number of effective channels will probably increase when improved measurements give better values for Γ_f.

We would finally mention qualitative evidence for this reaction in Pu^{240}. It has been shown from analysis of the fast-neutron–fission cross-section shape that fission takes place predominantly through the $\frac{1}{2}^-$ or $\frac{3}{2}^-$ states excited by p-wave neutrons.[10] Recent measurements made with a nuclear explosion used as a source of intense pulsed neutrons[11] confirm that fission in the slow-neutron resonances is strongly inhibited and is only about 1/100 of the capture process. Since the measurements of the capture and fission cross sections were made simultaneously with the same energy resolution, it is meaningful to compare the shape and peak heights of the cross-section curves. There is a striking similarity in the two partial cross sections, particularly below 200 eV, which implies a nearly constant value for the ratio Γ_f/Γ_γ. If Γ_γ is assumed to be constant, then the fission width varies little, indicating a large number of effective channels open for fission and thus also providing strong evidence for this reaction in Pu^{240}.

We believe that the data described here constitute substantial evidence that the $(n,\gamma f)$ reaction is present in Pu^{238} and that more accurate and complete studies on Pu^{238}, Pu^{240}, and other favorable nuclei should provide conclusive evidence of the existence of this reaction, and perhaps give quantitative information on the extent to which it is present.

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LOW-ENERGY THEOREMS AND INTERNAL SYMMETRY

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It is the purpose of this note to point out that the simultaneous use of (a) low-energy theorems and (b) internal symmetries leads to dynamical constraints without any approximation in regard to strong-interaction intermediate states. In other words, as we shall show first for isospin, then for SU(3), the simultaneous implementation of (a) and (b) leads to consistency conditions of a new kind which follow neither from (a) alone nor from (b) alone. When combined with nonsubtracted dispersion relations, the conditions take the form of integral relations between cross sections—see, e.g., Eqs. (5) and (8) below. They cannot, in general, be satisfied pointwise by cross sections at a given energy. We shall see in fact that they may interconnect with each other distinct multiplets of the internal symmetry.

As a first application, the truncation methods for sum rules will be discussed. Several attempts have been made recently to truncate cross-section integrals in sum rules by the approximation of the continuum by a finite set of more or less sharp resonant states. A main aim of this procedure is to find dynamical constraints which may serve to understand approximate dynamical symmetries such as SU(6). The consistency conditions are of interest for the understanding of the truncation method. It will be shown how they generate so-called "null solutions." An example of these is the following. It has been noted by many authors[1] that sum rules for the anomalous moments of the proton and the neutron give as a good lead-